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SEISMIC COMMUNICATION IN BASIN AND RANGE PROVINCE VALLEYS

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

It has long been recognized that the Earth provides a virtually inde-structible path of last resort for communicating with hard buried facilities. There is a need to establish the characteristics for communicating seismically in a landform suitable for MX deployment. We calculate the information rates for the seismic noise and response values measured at representative valley sites within the Basin and Range Province under the optimizing condition of constant reception spectra.

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CONTENTS

SEISMIC COMMUNICATION IN BASIN AND RANGE PROVINCE VALLEYS

1.   INTRODUCTION

1.1   Statement of Need

It has long been recognized that the Earth provides a virtually inde-
structible full duplex path for communicating with hard buried facilities (1).
Work on the subject has highlighted estimates of channel capacity for
communicating in competent rock (2), as well as the performance of specific
hardware and coding at short and long ranges (3,4).

There is a need to determine the information capacity for communicating
seismically in a landform suitable for basing MX (5). Of paramount interest
is the information rate for communicating seismically in deep, dry alluvial
valleys of the Basin and Range Province, the leading landform for MX basing.
To this end we establish the maximum information rate for sites in Railroad
Valley, Steptoe Valley and Jackass Flats, Nevada over a range of source
strengths, bandwidths and distances.

1.2.   Approach

We treat the Earth to be a linear, time invariant transmission path
defined by its Green's Function. Seismic signals observed at a distant
receiver point are delayed, colored versions of those generated by the source
masked partly by additive noise. For surface sources and surface observers,
seismic transmission at a distance is dominated by waves attenuated by Q
losses and cylindrical spreading.

Seismic noise at the candidate sites is well represented as stationary,
independent, Gaussian processes convolved with the appropriate site sensitive
shaping operators.

Maximum capacity seismic channels are computed after Hartley-Shannon

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for the seismic signals and noise terms found in each area. At high signal-to-noise ratios the optimum transmission channel is tantamount to matched filtering. The effect of source and receiver arrays on communication is also considered for the simple case of coherent signals and incoherent additive noise.

2. FINDINGS

Communication by seismic means is as commonplace as a "knock at the door"; its feasibility is not in question. What is in question is the capacity of seismic data links operated at specific source strengths and distances in the Basin and Range Province Valleys.

Information capacity for a ground path is readily calculated once the signal and noise spectra are specified. Data links can be optimized by weighting at the source and/or receiver. In any event, signal distortion due to seismic propagation can be nullified by a linear operator that is the inverse of the seismic impulse response, $G(r,t)$.

Seismic waves excited by surface impacts are well represented by unimodal Q damped surface waves. Under this representation signal spectra can be generated over any desired range of distances, source strengths and bandwidths.

The effect of range, bandwidth and source strength on channel capacity is established for the seismic signals and noise determined at each site. We find that seismic data links of 2 bits/second are quite realizable for distances of a few kilometers using sources of less than 100 Newtons rms in the band $2 \leq f \leq 20$ Hz.

The major uncertainty encountered when estimating capacity is caused by the uncertainty in Q and the presence of lateral inhomogeneities even in these seemingly simple valleys.

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3.   SEISMIC NOISE IN BASIN VALLEYS

3.1   Statistical Classification

Seismic noise is sensitive both to local ground structure and the kinds and distribution of noise sources. For sites excited by a large number of independent sources, we can anticipate Gaussian attributes. If the noise sources are also well distributed about an observer, the seismic noise field has well defined spacial properties for uniformly layered structures (6).

Figure 1 shows the distribution of the ground's particle velocity during quiet intervals at a site in Steptoe Valley near Ely, Nevada. The plot is arranged to give a straight line relation for Gaussian variates. The observed distribution is well represented by a zero mean, Gaussian process $N(o,s^2)$,s^2 = .02 (microns/sec)^2 (7). In remote areas, seismic noise tends to exhibit Gaussian attributes (8). The noise in the Basin and Range Province sites is not exceptional. Seismic noise in these rural valley areas also tests stationary (7,9). In contrast, noise in urban areas more often is non-stationary, reflecting the rhythms of the work cycle (8).

3.2   Spectral Estimates

Being both stationary and Gaussian, seismic noise at a point can be fully characterized by spectra (10). Figure 2 is a large average, spectral estimate of base level seismic noise measured in Railroad Valley. For frequencies much above 1 Hz, the spectra are relatively flat when cast into terms of particle velocity. The modest bulge in the spectra just above 10 Hz coincides with a loss of impedance of the ground to acoustic loads. The location of the frequency for generating air-coupled seismics is determined by the velocity and density structure neighboring the site.

For the sites considered, Railroad Valley is much the quietest. The seismic level here compares favorably to the level forecast for quality seismic detection sites in the southwestern United States (11). In turn, the seismic noise spectra at depth at these sites can be expected to be red versions of those measured at the surface in that the shorter wavelength, higher frequency components are almost always proportionately more attenuated at depth (12,13).

4. SEISMIC SIGNALS

4.1. Elastic Response

For an elastic body with homogeneous boundaries, the displacement at time, T', for a point located at $X'(x',y',z')$ relates to forces within a source volume located at X (x,y,z) acting at time, T, through the temporal convolution of the force with the appropriate Green function (14,15).

$$u_k(X',T') = \int_{-\infty}^{\infty}\!\!\!\int_V G_{ki}(X',T';X,T) * f_i(X,T)\,dv\,dt$$

In elastodynamics, the convention is to let a _displacement_ at a field point caused by _forces_ applied within the source region define response, Figure 3. The elastic response is causal, linear and time invariant. Also, when the source region is slowly moving and small with respect to the radiated seismic velocities and wavelengths, the source time history can be recovered by linear deconvolution (16). Further, source and field points can be exchanged in accordance with the reciprocity rule.

$$G_{ki}(X',T';X,T) = G_{ik}(X,-T;X',-T')$$

For uniformly layered areas and vertical surface loads, ground response

is insensitive to azimuth. Placing the source at the origin, we then express

response solely as a function of distance, r and retardation

time, t.

$$G(r,t)$$

4.2. Normal Mode Representation

We represent the Fourier transform of $G_{33}(r,t)$, the vertical displace-
ment of the ground surface at a "large" distance, r, due to a vertical impulse
at the origin, to be the sum of the normal mode contributions attenuated by a
material loss factor, Q,

$$G_{33}(r,\omega) = \sum_{j=1}^{N} A_j(\omega) \cdot r^{-\frac{1}{2}} \exp \ (-k_j(\omega) \cdot r)/2Q(\omega) \cdot \exp \ i \ (k_j(\omega) \cdot r + \emptyset_j(\omega) \ )$$

Here j is the mode number and A, $\emptyset$ are the apparent amplitude and phase

associated with the source. As given here, attenuation is governed by

cylindrical spreading and a spacial Q loss defined by the fractional loss of

amplitude over one wavelength. The spacial Q term used here relates to a

temporal determination of Q through the relation,

$$Q^{-1}(\text{temporal}) = \frac{U}{c} \cdot \ Q^{-1}(\text{spacial})$$

with c, U the phase and group velocities of the mode in question.

For our test sites experimental values of $G_{33}(r,\omega)$ are fitted to a

fundamental mode representation by determining A,k,$\emptyset$,Q over a discrete

distance set, r_ℓ, $\ell = 1,2,3...$

4.2.1. Propagation

The average value for unit amplitude, k' weighted surface impacts over the distance, r_ℓ, = 1,2,3,..,L is

$$F_{33}(k',\omega) = 1/L \sum_{\ell=1}^{L} G_{33}(r_\ell, \omega) \cdot \exp(-ikr_\ell) \cdot |G_{33}(r_\ell, \omega)|^{-1}$$

$F_{33}(k',\omega)$ has a maximum value of unity for unimodal, low noise measurements when $k' = (\omega/c)$. Figure 4 is a sample computation of $F_{33}(k',\omega)$ based on 50 response wavelets measured over the range $120 \leqslant r \leqslant 200$ meters. The calculated, maxima are quite close to unity over the pass band $3.7 \leqslant f \leqslant 37$ Hz; the seismic response at the site can be well represented by a unimodal surface wave for these frequencies. Figure 5 locates the (k',ω) pairs that generate absolute maxima for the data; the relation establishes the propagation characteristics at the test site. The phase and group delay times are determined from $c = \omega/k$ and $U = d\omega/dk$

$$t_p = r/c \qquad t_g = r/U$$

4.2.2. Source Phase

Once k' is determined, source phase is calculated directly from the residual phase at r=0.

$$\text{ARG}\left(G_{33}(0, \omega)\right) = \text{ARG}\left(G_{33}(r, \omega)\right) \cdot \exp(ik'r)$$

In Figure 6 the average phase residuals over reliable (k, ω) pair values are independent of frequency. The theoretical value for cylindrically spreading surface waves due to a surface impact on a uniformly layered elastic half space at large distances, r, is $\pi/4$. The calculated source term is consistent with the normal mode representation used here.

4.2.3. Attenuation

For unimodal propagation in uniformly layered, lossy media, surface wave attenuation at a distance can be obtained from

$$\left| G(r, \omega) \right| = A(\omega) \cdot 1/r^{\frac{1}{2}} \cdot \exp(-kr/2Q)$$

In Figure 7 we plot $\ln \left| G(r, 50)r^{\frac{1}{2}} \right|$ for each of 63 impact wavelets measured in Jackass Flats as they relate to distance. Q is then calculated from the slope of the best fitting (least square) slope of the data. A measure of the goodness of fit, E , is also calculated from the residuals.

Figure 8 shows our estimate for Q and E for Jackass Flats as they relate to frequency. Q estimates tend to be decreasing functions of frequency. A Q of 35 in surficial sediments is modestly larger than Q values used elsewhere (1).

4.2.4. Prediction Errors

The dispersion relation and Q values found for Railroad Valley are used to adjust individual impulse responses over $100 \leq r \leq 200$ meters to a common reference distance, r=150. The average amplitude response for 150 meters, [G(150,f)] ave is then obtained, see Figure 9. The ground is found to be a band pass transmission element. The low limb is controlled by the nature of the elastic response. The high limb roll off is dominated by the material quality factor, Q.

The ground disturbance predicted in Railroad Valley for a standard impulse as it relates to distance is given in Figure 10. The synthetic responses shown here obey the A,k,ϕ,Q parameters calculated at the site for unimodal surface waves in the range, $100 \leq r \leq 200$ meters.

The synthetic waveforms are compared to the actual wavelets. Error

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wavelets, the difference between predicted and measured values, are quite small, Figure 11. The error is ascribed to additive seismic noise, higher mode responses and lateral inhomogenities.

The scatter in the individual amplitude and phase responses about an average value for Jackass Flats is given in Figure 12. Scatter diagrams such as these are used to support the proposition that the original measurements are heavily corrupted by additive noise for frequencies greater than 35 Hz. (16).

It is worth noting that the predicted seismics at distances greater than a few hundred meters are quite sensitive to our estimate of Q. A unit difference in Q causes about a 6 db difference in the predicted midband amplitude response at 1 km. Indeed, a major impetus for this study has been the lack of reliable attenuation data in Basin and Range Valley materials. Recent interest in mantle Q permits an upgrading of earlier work concerning communicating seismically at long range (4); it bears little on data rate estimates at modest distances (10km) for the deep alluvial valleys in the Basin and Range Province.

Even in these supposedly simple valley sites, attenuation is due to lateral structural changes as well as Q losses. To show this we determine the phase velocity for a number of headings in Railroad Valley, Figure 13. The seismic response at this site is found to be azimuth sensitive. Ground structure is not laterally uniform. Attenuation is not soley a function of distance and Q loss. As can be seen, the effect of heading is somewhat less severe at lower frequencies, suggesting the valley is more uniform at depth.

5.   CHANNEL INFORMATION RATES

The capacity of a communication channel in bits/sec over the band $a \leq f \leq b$ is computed after Hartley-Shannon as

$$C = \int_a^b \log_2 \left[\frac{P_{ss} + P_{nn}}{P_{nn}} \right] df$$

where P_{ss} and P_{nn} are the power spectra of the signal and noise processes, respectively (18). Channel capacity is a maximum when $P_{ss} + P_{nn}$ = constant. Constant reception spectra can be obtained either by weighting at the source or receiver. In either case we can negate distortions due to the seismic path by application of a linear convolution operator that is the inverse of the ground response, $G(r,t)$.

5. 1. Narrowband Sources

The center frequency for minimum strength sources and optimum transmission is illustrated for the transmission and noise characteristics in Railroad Valley. Figure 14 is the $P_{ss}(f)/P_{nn}(f)$ ratio for a white source of strength, $S = 6.25$ Newtons rms measured at a range of 150 meters. P_{ss}/P_{nn} is a maximum near 18 Hz. In this case a channel centered at 18 Hz is optimum in the sense that it maximizes channel capacity for a given source level, band-width and range.

In order that the maximum channel capacity for broadband sources be realized, the inverse of the path response must be known. Even the detection of signals with a peak G_{ss}/G_{nn} substantially less than unity is not without difficulty. The capacity of channels, using one or more transmitter-receiver pairs uncompensated for seismic dispersion, passes a sub optimally coded sequence.

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The maximum information capacity for a source of 31.25 Newtons rms and 1 Hz bandwidth is determined for Railroad valley. From Figure 15 we find we can transmit and receive in excess of 2 bits/second over a 1 Hz band at a distance of 1 km using a source of only 31.25 Newtons rms.

After a range of a few hundred meters, narrowband sources are relatively efficient seismic transmitters. In Figure 16 the effect of source bandwidth and range on information capacity is shown for a source strength of 9.375 Newtons rms. For this source level and locality, a bandwidth of 3 Hz is optimum at a range of 0.50 km.

In Figure 17 we determine the source strength needed to maintain a channel capacity of 2 bits/second over a bandwidth of 1 Hz. A source level of at least 25 Newtons rms is needed to insure a channel capacity of 2 bits/second at a range of 1 km. Under these constraints an approximately linear relationship exists between source strength and distance.

5.2   Broadband Sources

The information rate for a channel consisting of a broadband signal source and a receiver whose response is the inverse of that of the ground is depicted in Figure 18 for a range of 150 meters and source strength of 4.419 Newtons in the band of 50 Hz. The plot shows seismic communication to be a low pass phenomenon in that 95% of the channel capacity is obtained from frequencies less than 35 Hz. The bandwidth for efficient seismic communication is also range dependent. To show this we compute the cutoff frequency needed to attain 98% of channel capacity for white sources, Figure 19. The useful information bandwidth for weak sources at distances greater than 1 km is less than 20 Hz in Railroad Valley.

To further show the impact of range on broadband communications, we

estimate channel capacities in Railroad Valley as they relate to bandwidth over a suite of distances, Figure 20. Broadband seismic communications require relatively strong sources to excite frequencies much above 25 Hz for distances greater than 200 meters.

6.   TRANSMITTER AND RECEIVER ARRAYS

Coherent signals embedded in additive incoherent noise provide a conservative basis to estimate the effect of both transmitter and receiver arrays on channel capacity. For such a construction P_{ss}/P_{nn} increases directly as the sum of the number of receiver and transmitter elements. Channel capacity for systems employing multiple transmitter and receiver elements is shown in Figure 21 for narrowband transmissions at a range of 300 meters.

The prospects of surface arrays separating signals from noise are considerably better for buried sources than for surface sources. The reason for this is that both the noise and signals excited by surface sources propagate largely as low order surface waves. Arrays cannot separate seismic waves traveling in the same direction with the same mode. In contrast, low mode surface seismics are only poorly excited by buried sources. Arrays using velocity filtering should be quite effective for separating seismic signals from noise in the case of buried sources (19).

7.   SITE EFFECTS

In Figure 22 the seismic wavelets produced by a standard impact at a distance of 150 meters are shown for Jackass Flats and Railroad valley. Seismic response is clearly site sensitive. It immediately follows that channel data rates are also site sensitive. Optimum capacity channels for a broadband transmitter in Jackass Flats is given in Figure 23. For the ranges

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and frequencies considered, Railroad Valley has the greater capacity. Low noise in Railroad Valley is the controlling factor.

All the estimates given in this study are for point surface sources and surface receivers. For a surface source and a buried receiver at large offset distances both the noise and signal are attenuated in roughly similar fashion. P_{ss}/P_{nn} ratios at depth should be much the same as those found for surface sources and receivers. The results of this study should apply. In contrast, P_{ss}/P_{nn} should be significantly smaller for a source at depth and a surface receiver. Reliable assessments for communicating to the surface from a buried facility requires seismic measurements at depth in the areas of interest.

8. REFERENCES

1. An Estimate of the Maximum Range of Detectability of Seismic
   Signals, N.A. Haskell, Air Force Survey in Geophysics No. 87, March
   1957, AFCRL-TN-57-202, AD152610.

2. Seismic Communications Feasibility Study, Don R. Fink, Park H. Miller,
   Philco-Ford Blue Bell, PA Communications and Electronics Div., May 1968,
   AD391651

3. Continuous Seismic Wave Communications Experiments at 80 Hz in
   Diverse Terrains, R.F. Johnson et al, U.S. Army Electronics Command
   Research and Development Technical Report ECOM- 2921, January 1968,
   Fort Monmouth, N.J., AD832794.

4. Study of the Feasibility of Long-Range Seismic Communications, July 72
   H.W. Briscoe, Report No. 2405, Bolt Beranek and Newman, AD 904729.

5. Technical Exchange Meeting at BMO, Norton AFB, California, June
   1982, Lt. Col. M. Jackson.

6. Space and Time Spectra of Stationary, Stochastic Waves with
   Special Reference to Micro-Tremors, K. Aki, BERI Vol. 35, 1957.

7. Temporal Attributes of Seismic Base Noise in Steptoe Valley, F. Crowley,
   H. Ossing, E. Hartnett, AFGL-TM-40, 1980.

8. Earth Environmental Noise Fields, F.A. Crowley, H.A. Ossing, Air
   Force Surveys in Geophysics No 224, AFCRL 70-0460, 1970, AD 713172.

9. Temporal Attributes of Seismic Base Level Motion, Railroad
   Valley, Nevada, H.A. Ossing, Eric B. Carleen, AFGL-TR-81-0221, 1981.

10. Topics in the Theory of Random Noise, Volume 1, RL Stratonovich, Gordon
    and Breach, New York, 1963.

11. A Survey of the Ambient Motion Environment in the Southwestern United
    States, H.A. Ossing, R.A. Gray, AFGL-TR-78-0052, February 1978, ADA056872.

12. Noise Attenuation in Shallow Holes, E.J. Douze, The Geotechnical
    Corporation, Technical Report No. 64-135, 11 January 965.

13. Study of Seismic Signals and Noise by Means of a Buried Array,
    G.C. Phillips, Changsheng, Wu, AFCRL-TR-66-578, June 1966, AD 637687.

14. Moment Tensors and other Phenomenological Descriptions of Seismic
    Sources. Backus G., 1976. Geophys. Journ. Res. Astro. Soc.

15. Quantitative Seismology. Aki, K., 1980., W.H. Freeman and Company.

16. The Determination of Source Properties, Stump, B., 1977, BSSA.

17. Seismic Transmission in Jackass Flats and Steptoe Valley, Nevada,
    Crowley, F., Hartnett, E., Ossing, H., AFGL-TR 82-0023, 1 December 81.

18. Principles of the Statistical Theory of Communication, Harman, W. W.,
    Mc Graw-Hill, New York, 1963.

19. Seismic Detection and Location of Isolated Miners-Final Report, Arthur
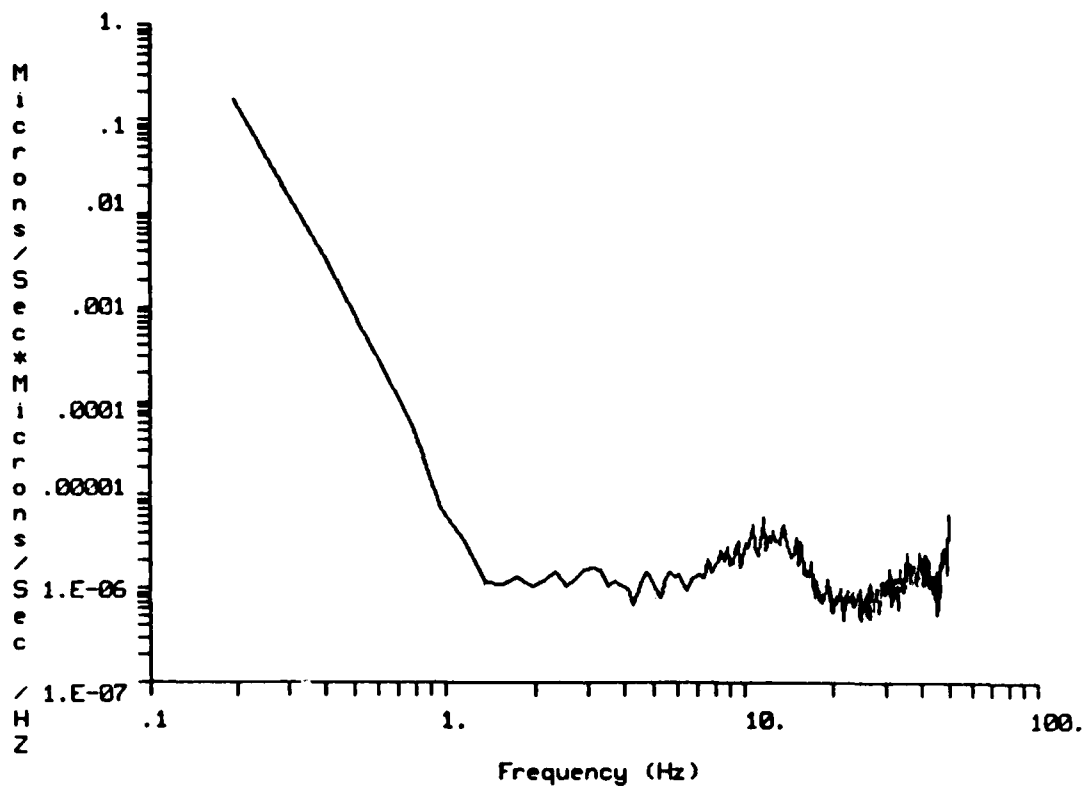   D. Little. Contract No.122026 -15 December 1972.

FIGURES

VERTICAL PARTICLE VELOCITY

microns/second x(.02)$^{\frac{1}{2}}$

1.0

0

1.0

$N(0,S^2)$

$S^2 = .02\left(\dfrac{\text{microns}}{\text{second}}\right)^2$

1   10   20   40   60   80 90 95   99

DISTRIBUTION: %

SEISMIC NOISE DISTRIBUTION- STEPTOE VALLEY

Figure 1

SEISMIC NOISE SPECTRA: RAILROAD VALLEY

Figure 2

u_k ~ DISPLACEMENT $\qquad$ f_i ~ FORCE

$$u_k(X',T') = \int\limits_{-\infty}^{\infty}\int\limits_{V} G_{ki}(X';T';X,T) * f_i(X,T)\, dV\, dT$$
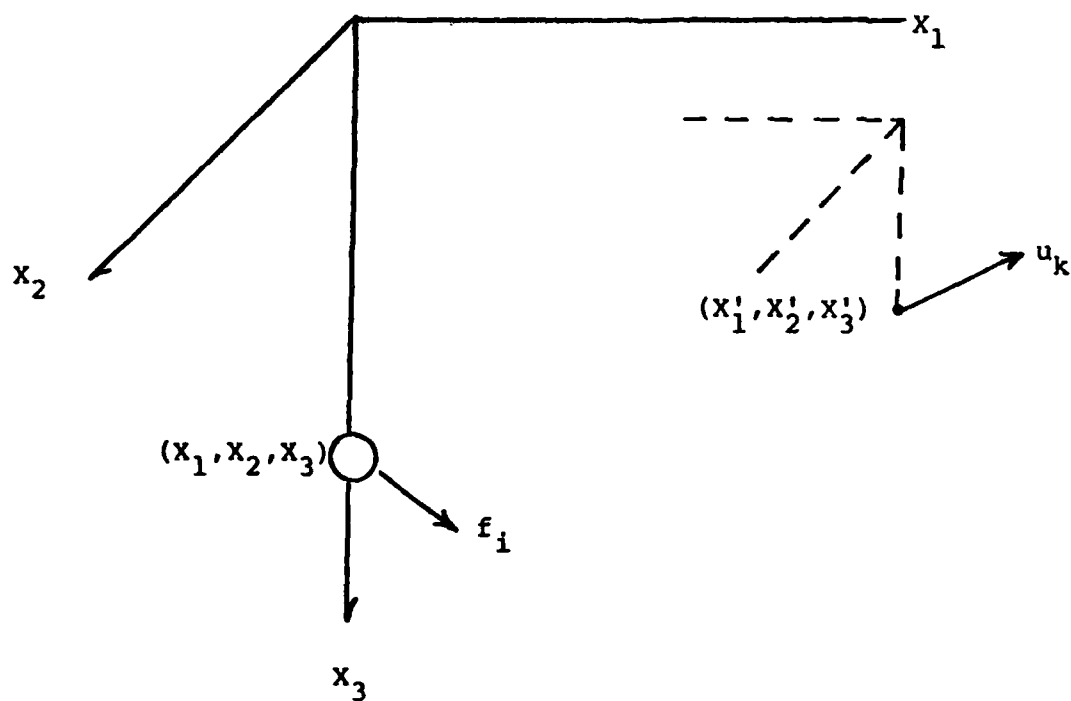
* TEMPORAL CONVOLUTION

GREEN'S FUNCTION REPRESENTATION

Figure 3

$\left| F_{33}(f) \right|$

MAGNITUDE

North: RRV

ANGULAR FREQUENCY $(2\pi f)$

QUALITY OF UNIMODAL MODEL

Figure 4

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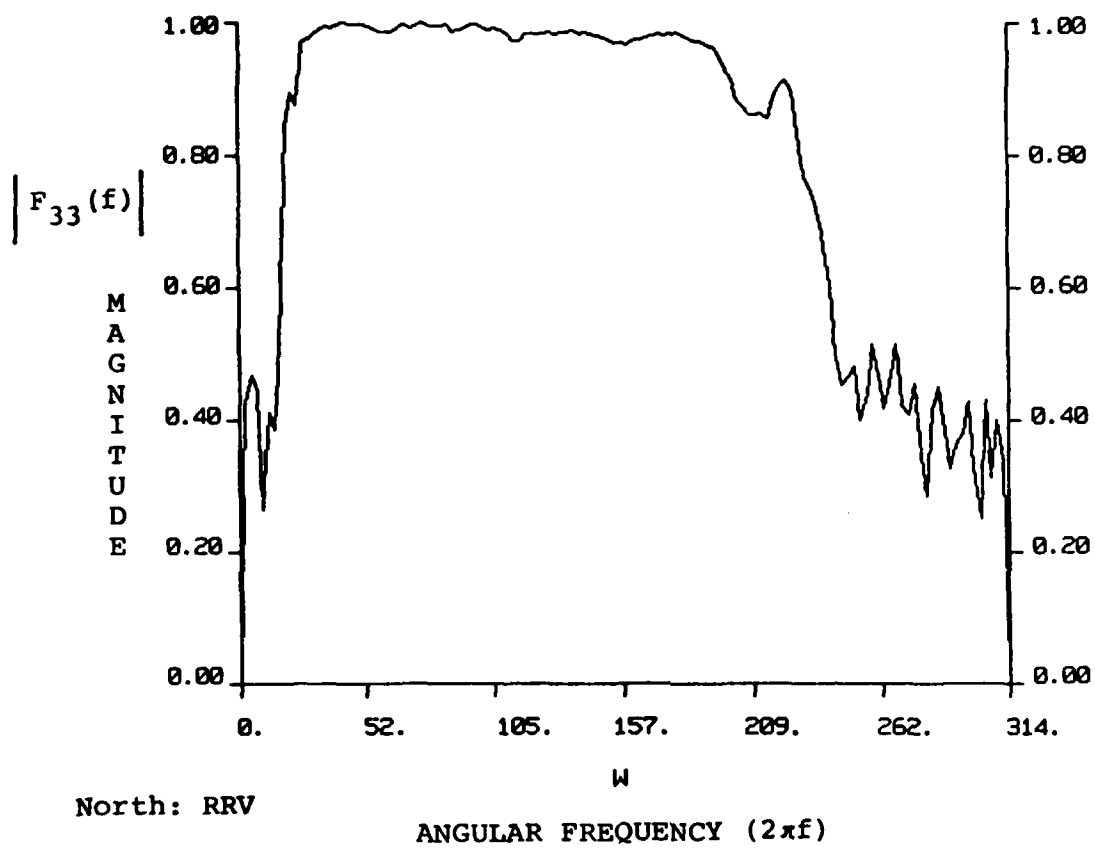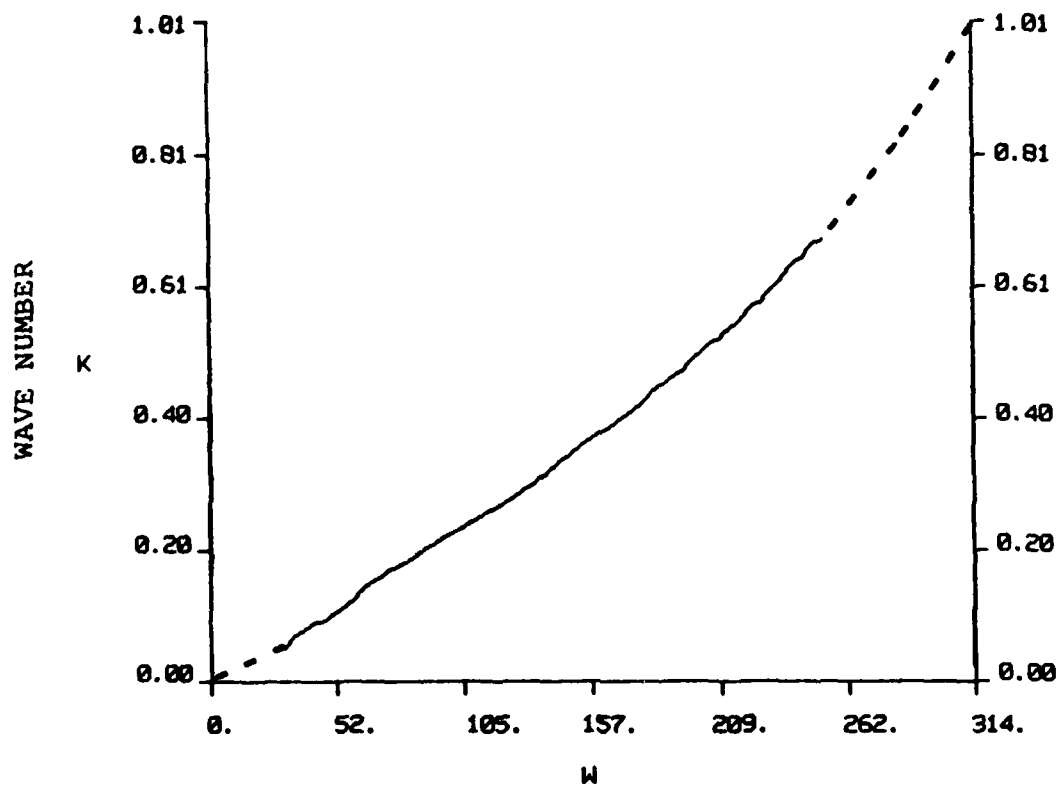
North RRV

ANGULAR FREQUENCY (2×f)

MEASURED DISPERSION

Figure 5
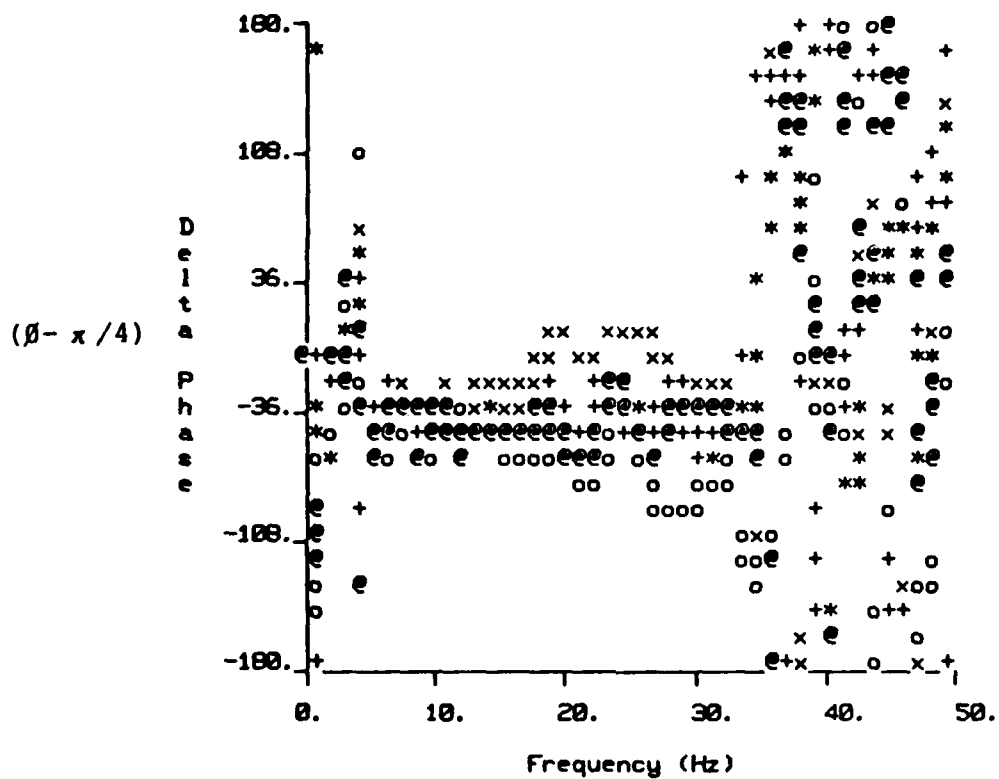
DELTA PHASE (Corrected for + $\pi/4$)

SOURCE PHASE

Figure 6
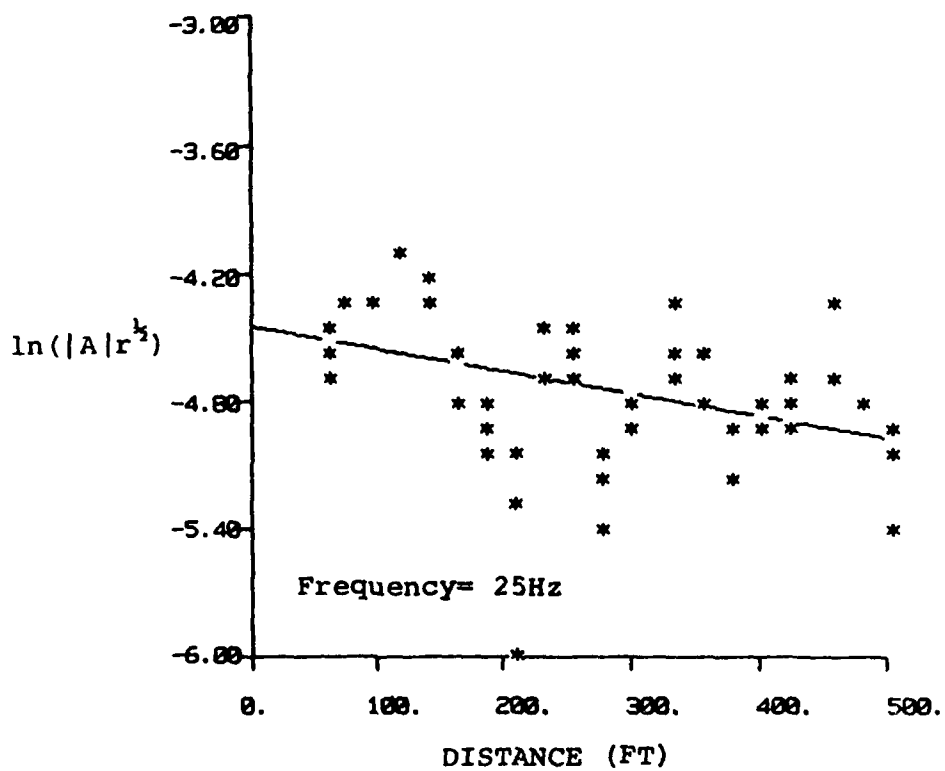
ATTENUATION: ETB

Figure 7

26
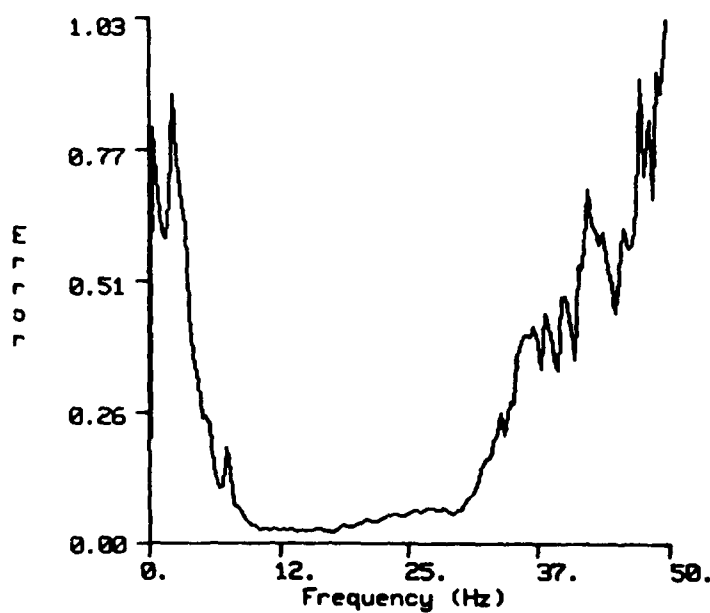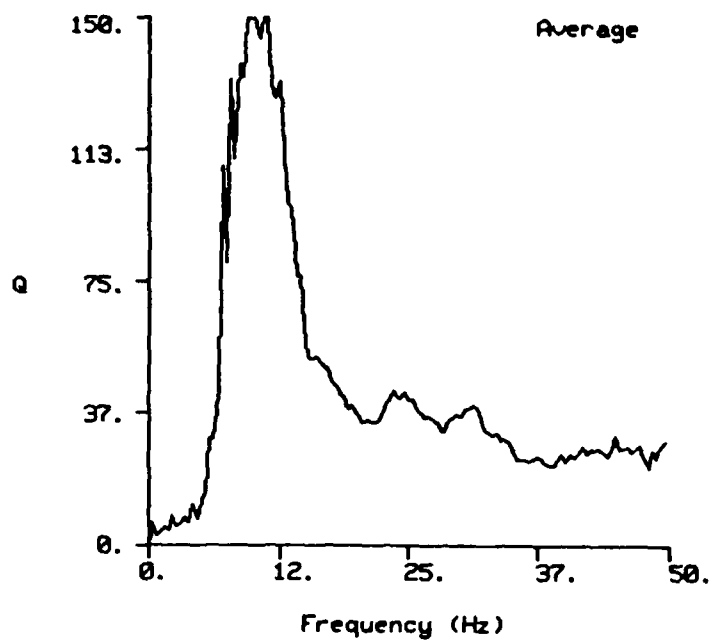
Q ESTIMATES

Figure 8
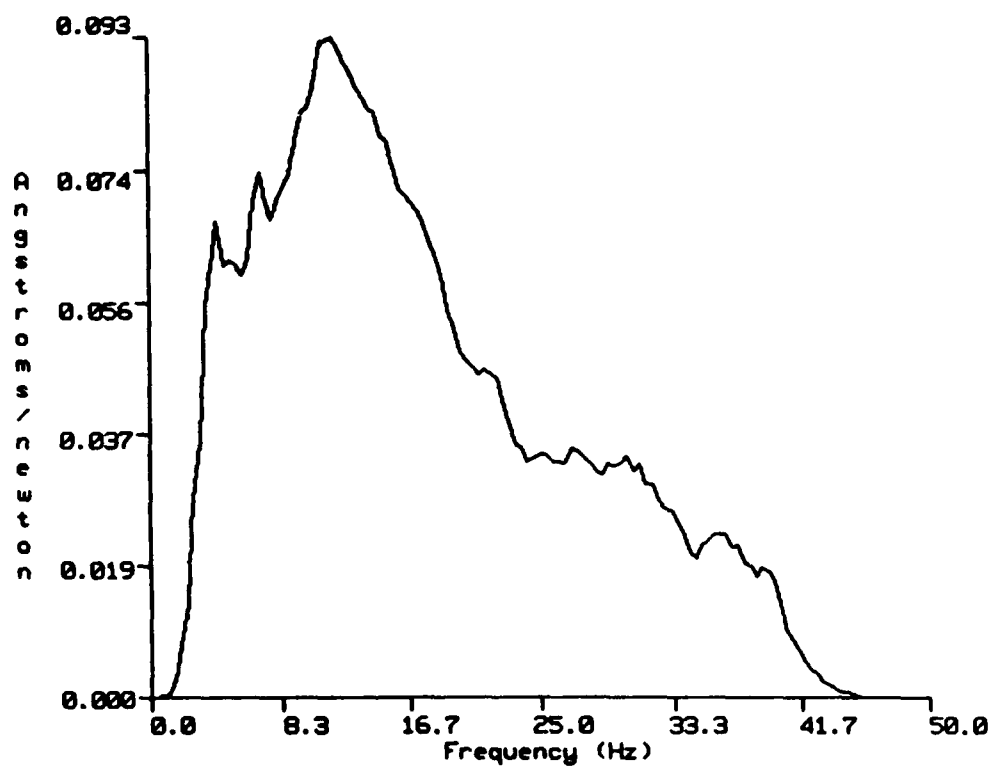
AVERAGE AMPLITUDE RESPONSE

Figure 9

GROUND DISPLACEMENT

DISTANCE
(meters)

ANGSTROMS
(per Newton)

150 .... 0.0108

-0.0327

300 .... 0.00675

-0.00915

450 .... 0.00469

-0.00371

600 .... 0.00284

-0.00214

750 .... 0.00211

-0.00114

900 .... 0.00148

-0.00104

0.000 1.024 2.048 3.072 4.096 5.120

Time (secs.)
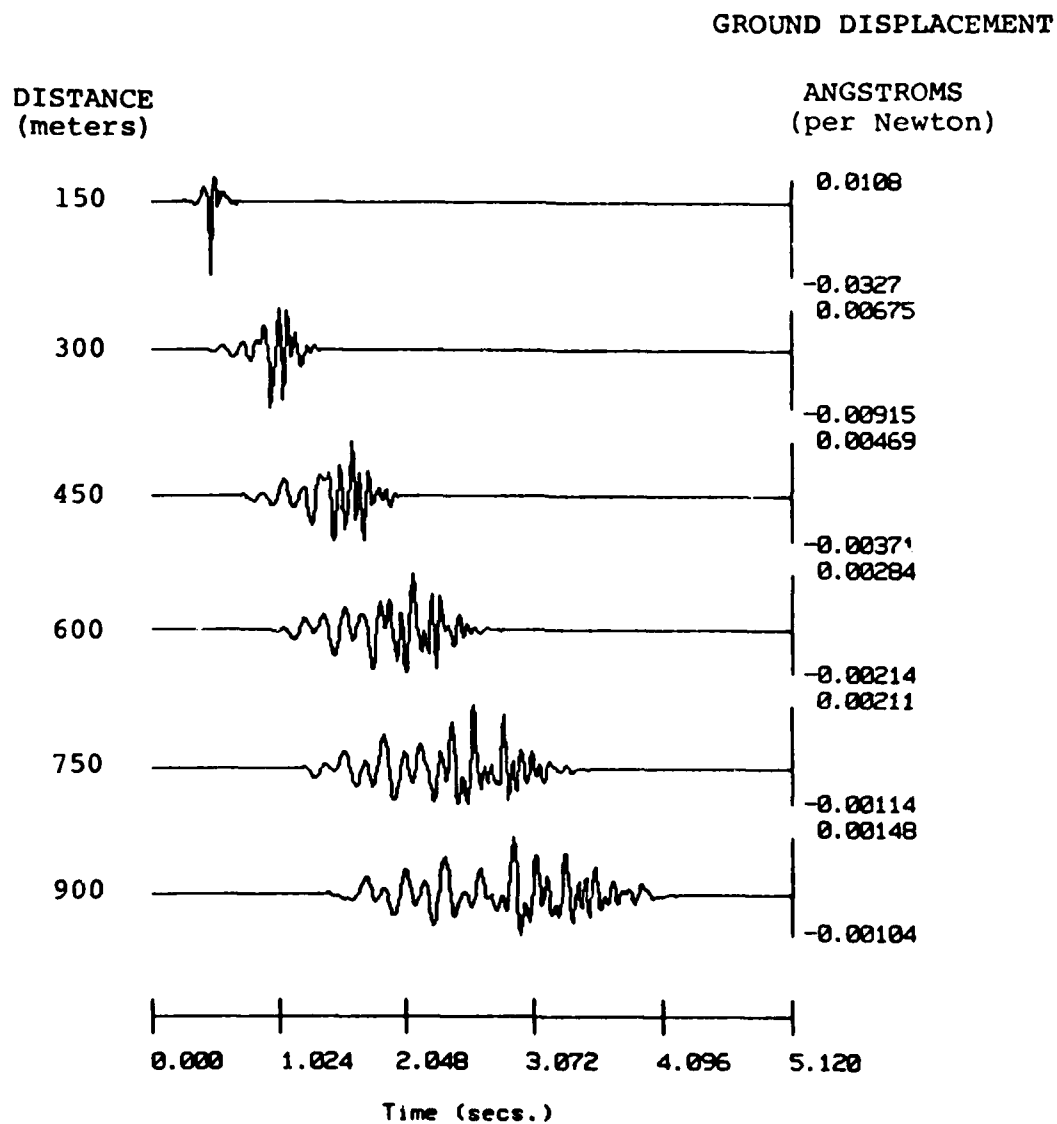
PREDICTED RESPONSE-RAILROAD VALLEY (270°)

Figure 10

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Railroad Valley 270°

Response to a hammer blow

Distance 150 meters
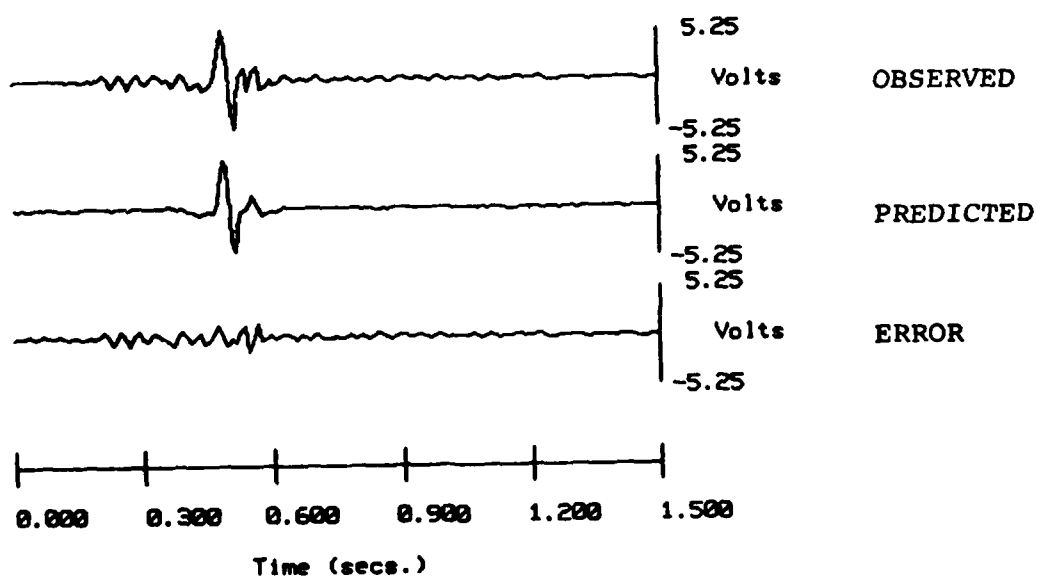
ERROR WAVELET

Figure 11
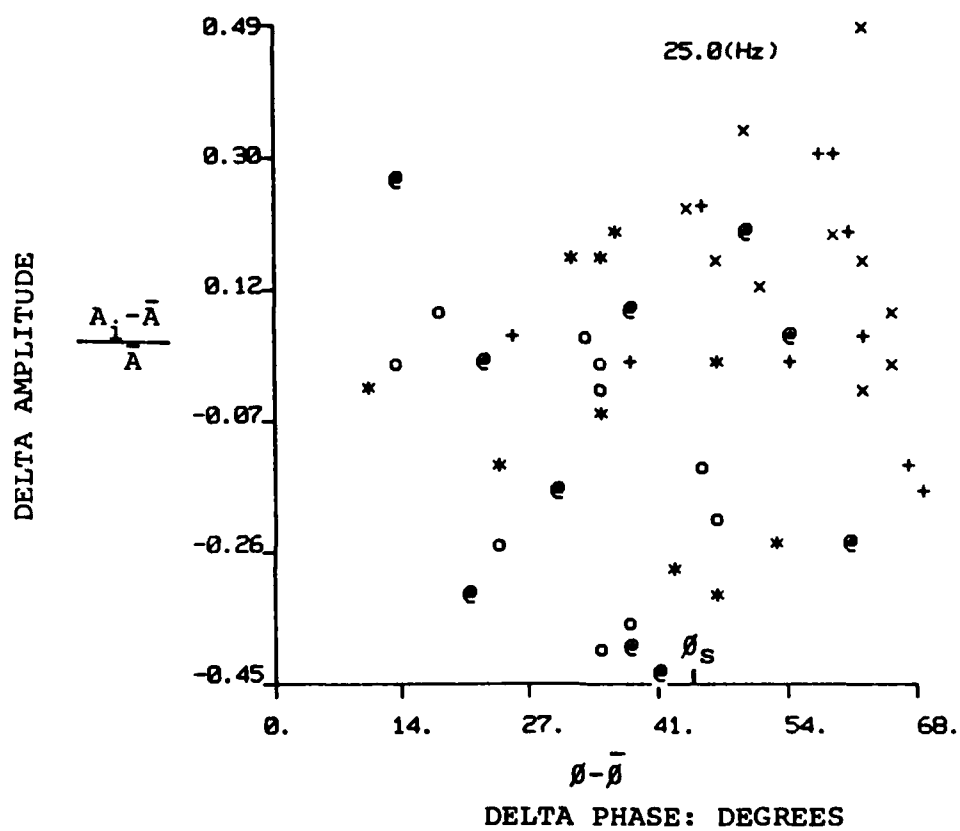
AMPLITUDE AND PHASE SCATTER: 25 Hz

JACKASS FLATS
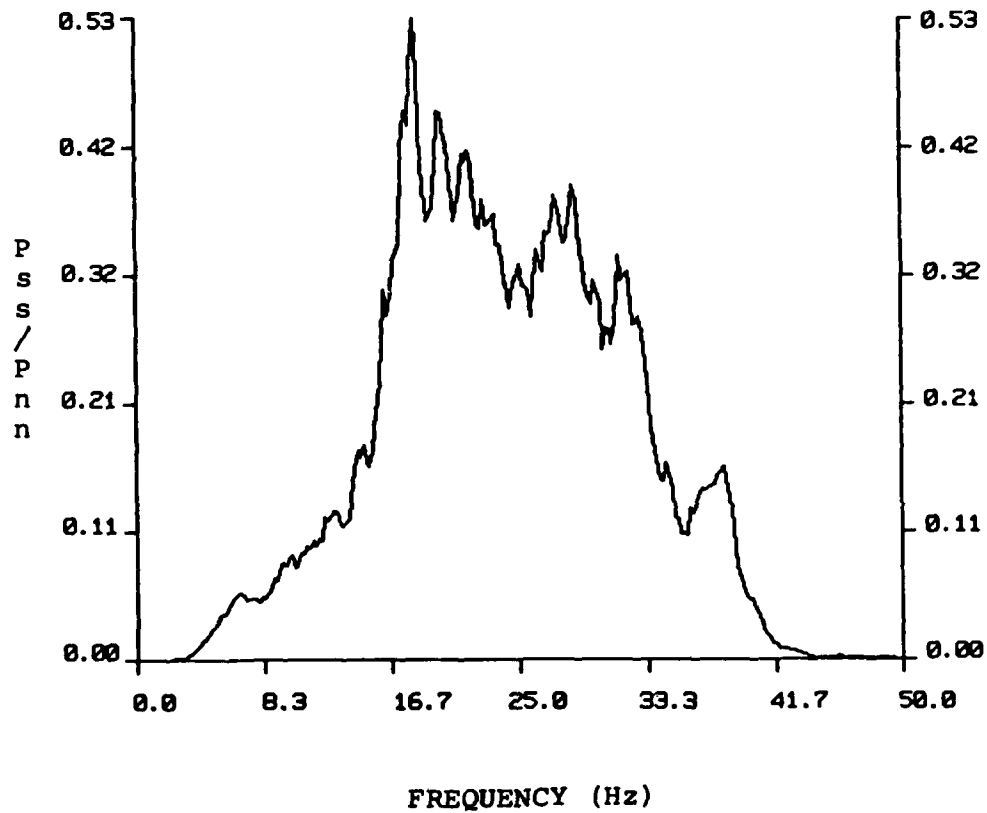
Figure 12

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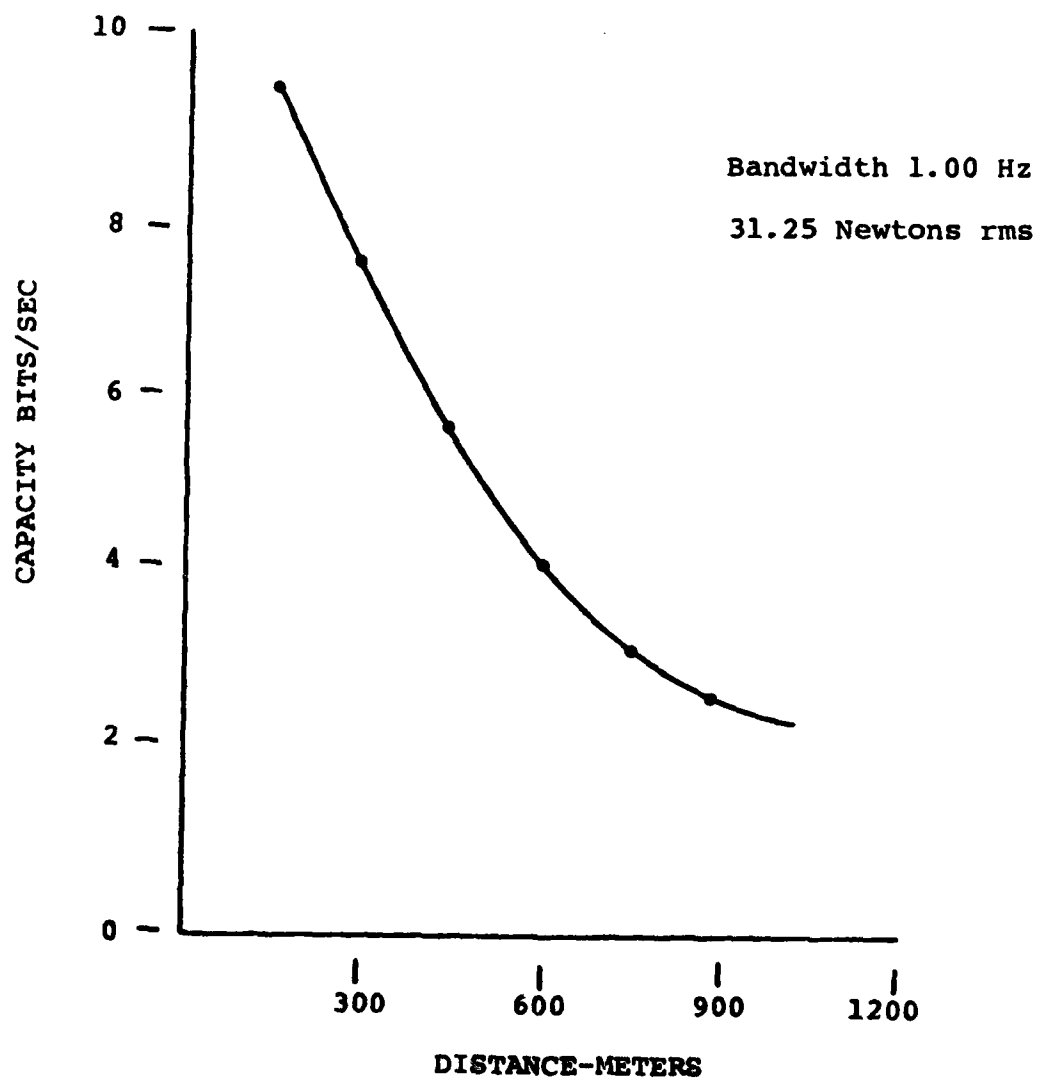LATERAL INHOMOGENEITIES IN RAILROAD VALLEY
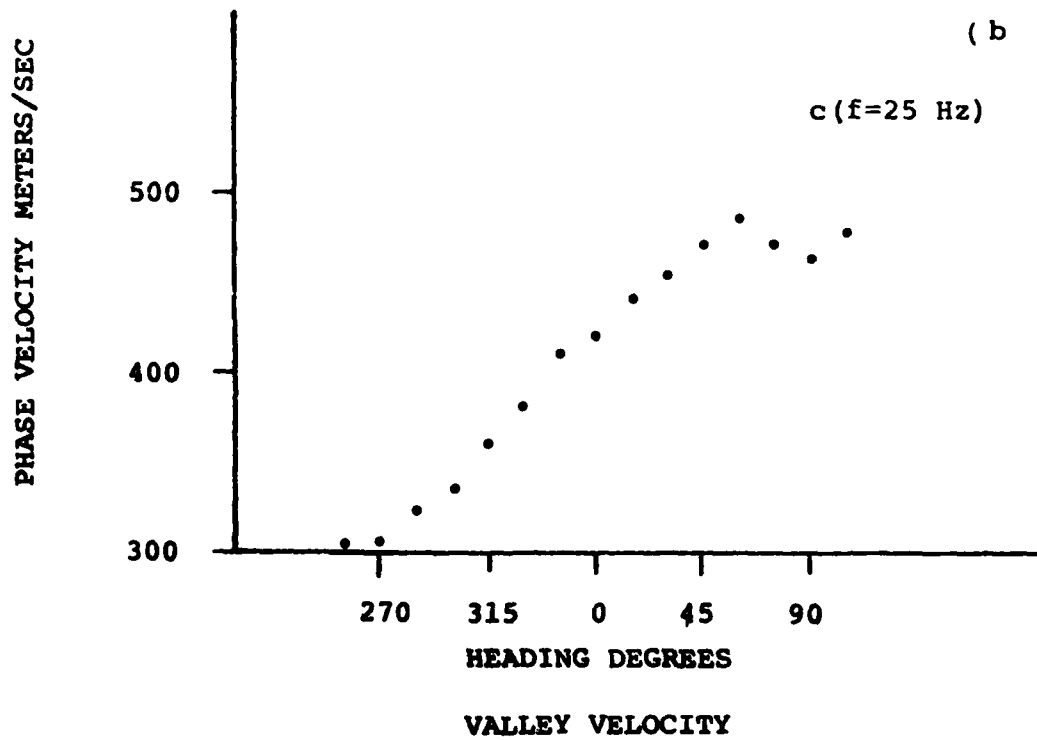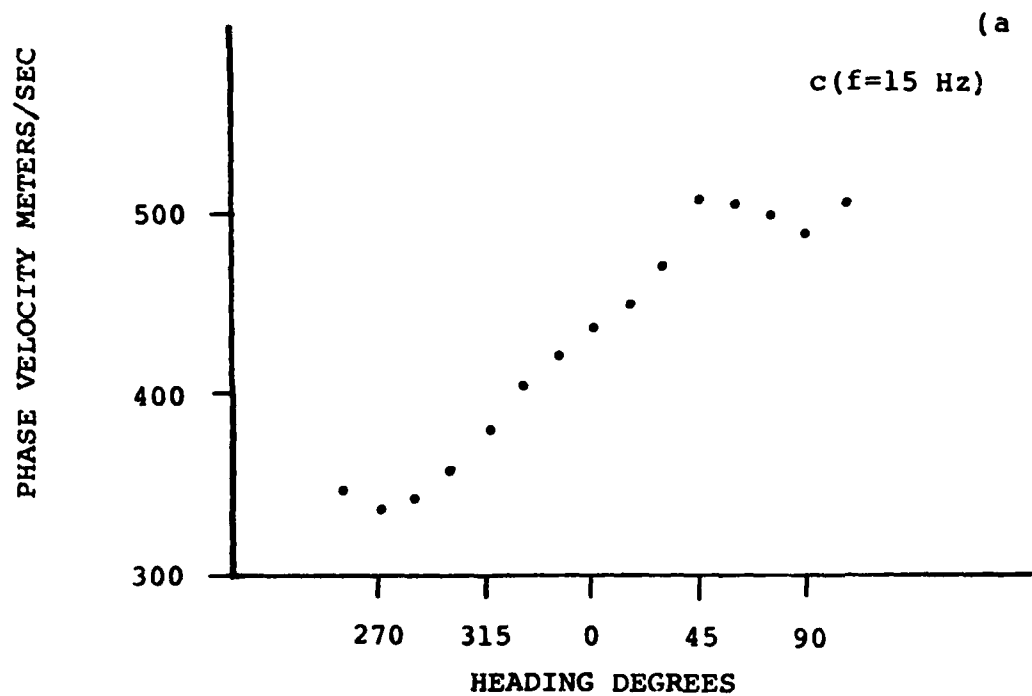
Figure 13

Bandwidth 50 Hz

Source 6.25 Newtons rms

FREQUENCY (Hz)

P_{ss}/P_{nn} RATIO; RRV 150 METERS

Figure 14

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Bandwidth 1.00 Hz

31.25 Newtons rms

CHANNEL CAPACITY: RRV (270°) NARROW BAND SOURCE

Figure 15
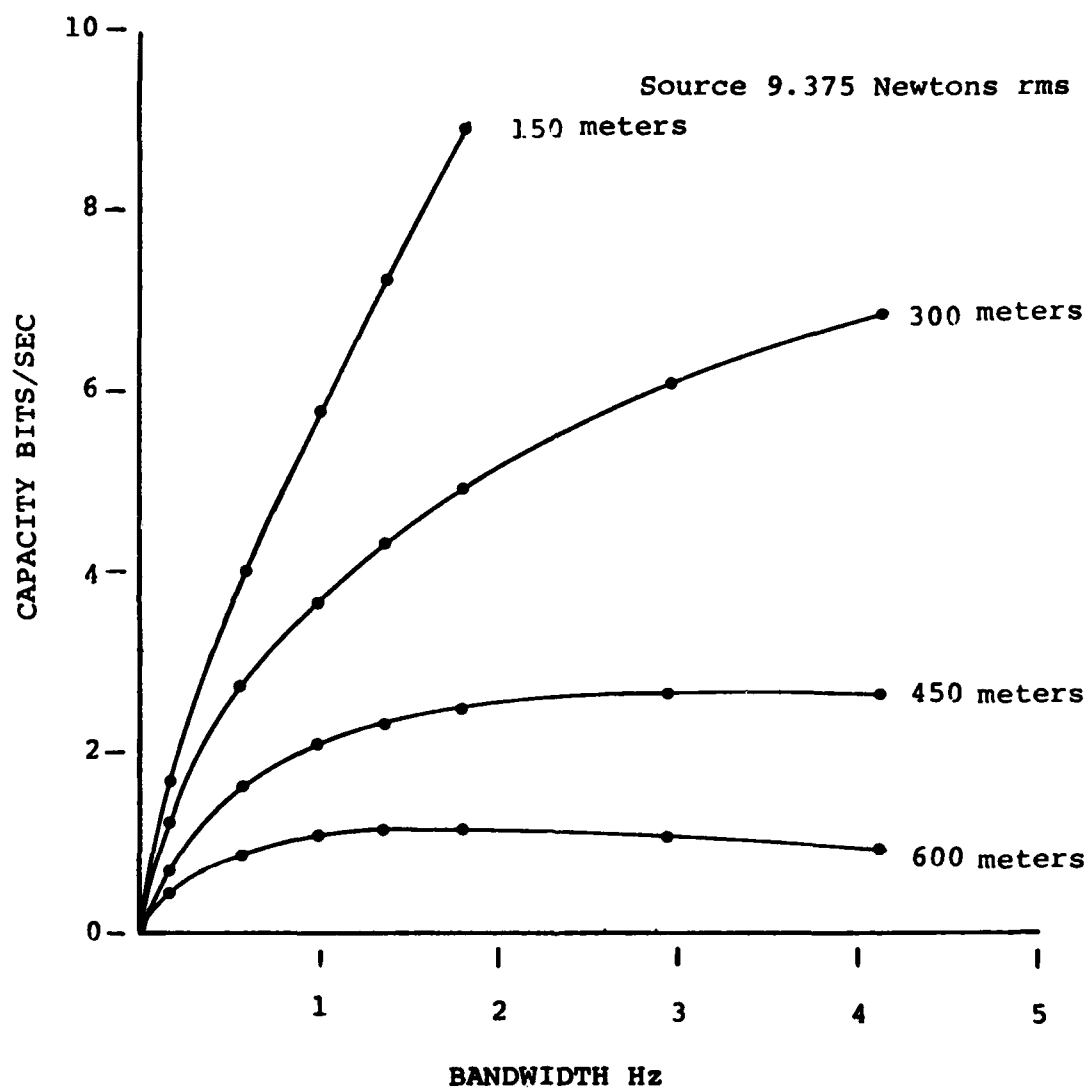
EFFECT OF BANDWIDTH

Figure 16

Bandwidth 1 Hz
Capacity 2 Bits/Sec
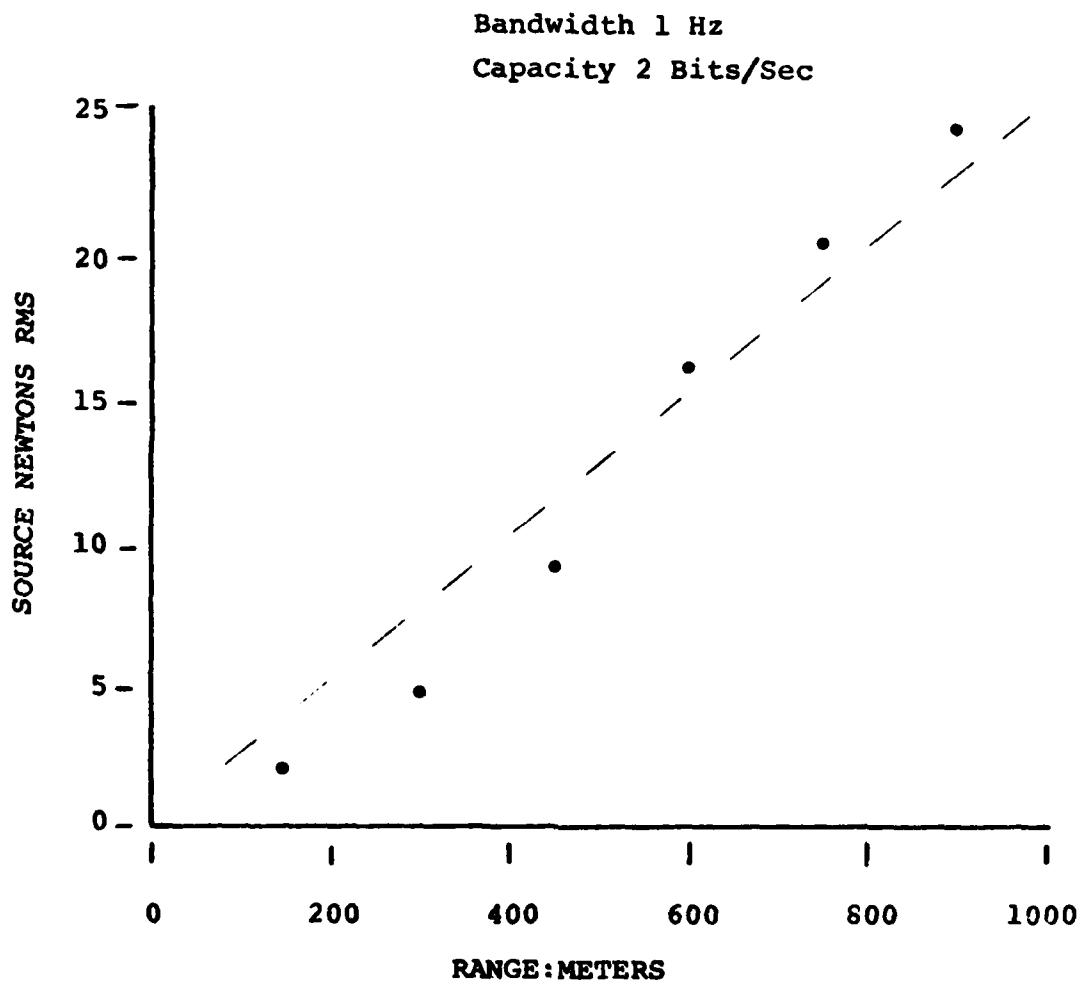
EFFECT OF SOURCE STRENGTH

Figure 17

SOURCE 4.419 Newtons rms
Bandwidth 50 Hz
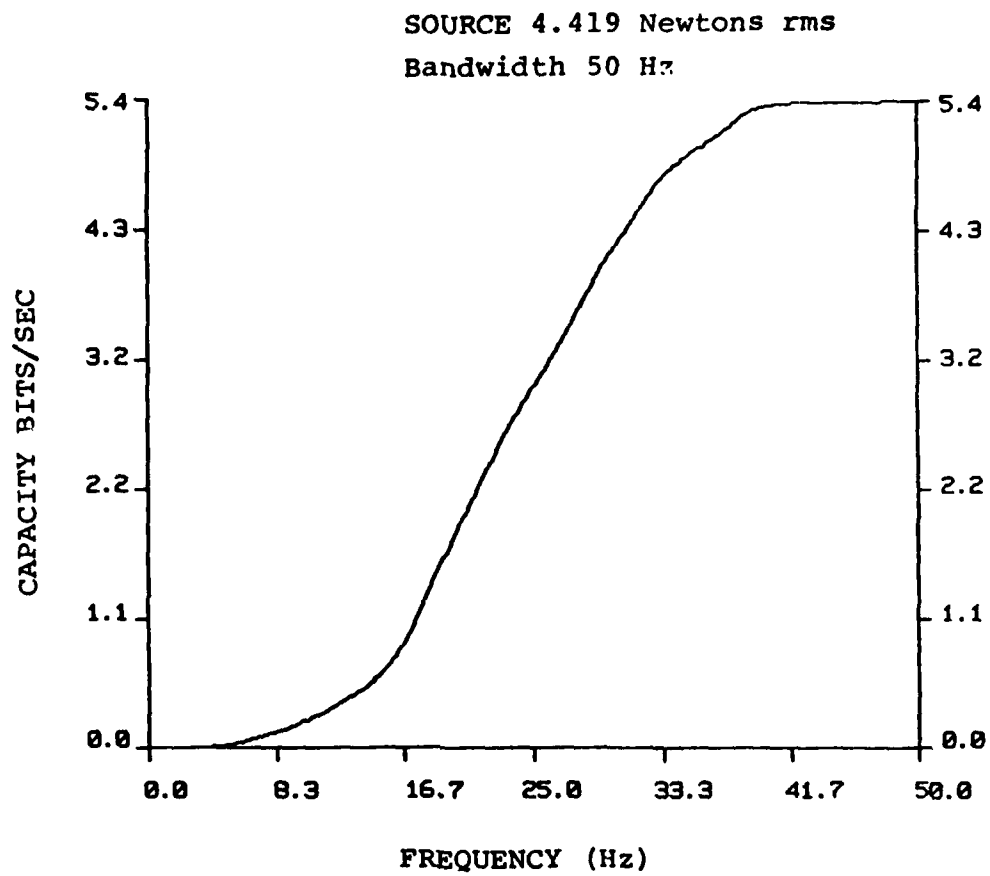
GROUND BANDPASS CHARACTERISTIC: RRV 150METERS

Figure 18

Useful Bandwidth (98%)
Source 31.6 Newtons rms
Bandwidth 0-50 Hz

DISTANCE METERS

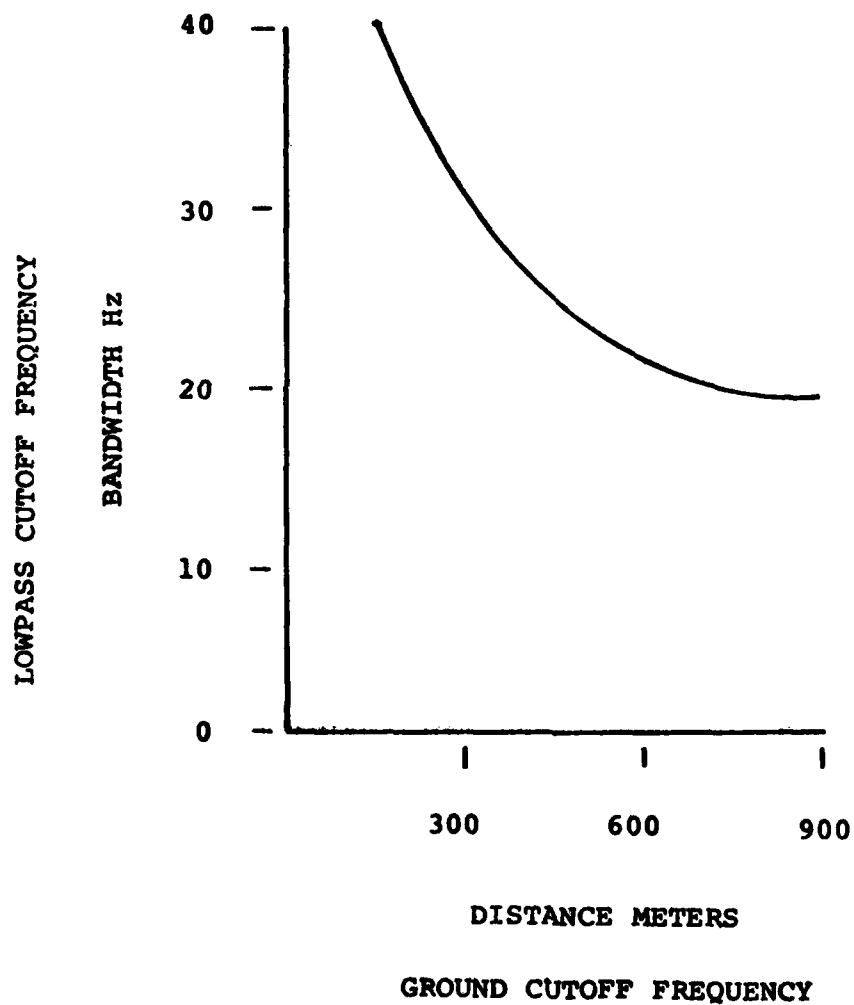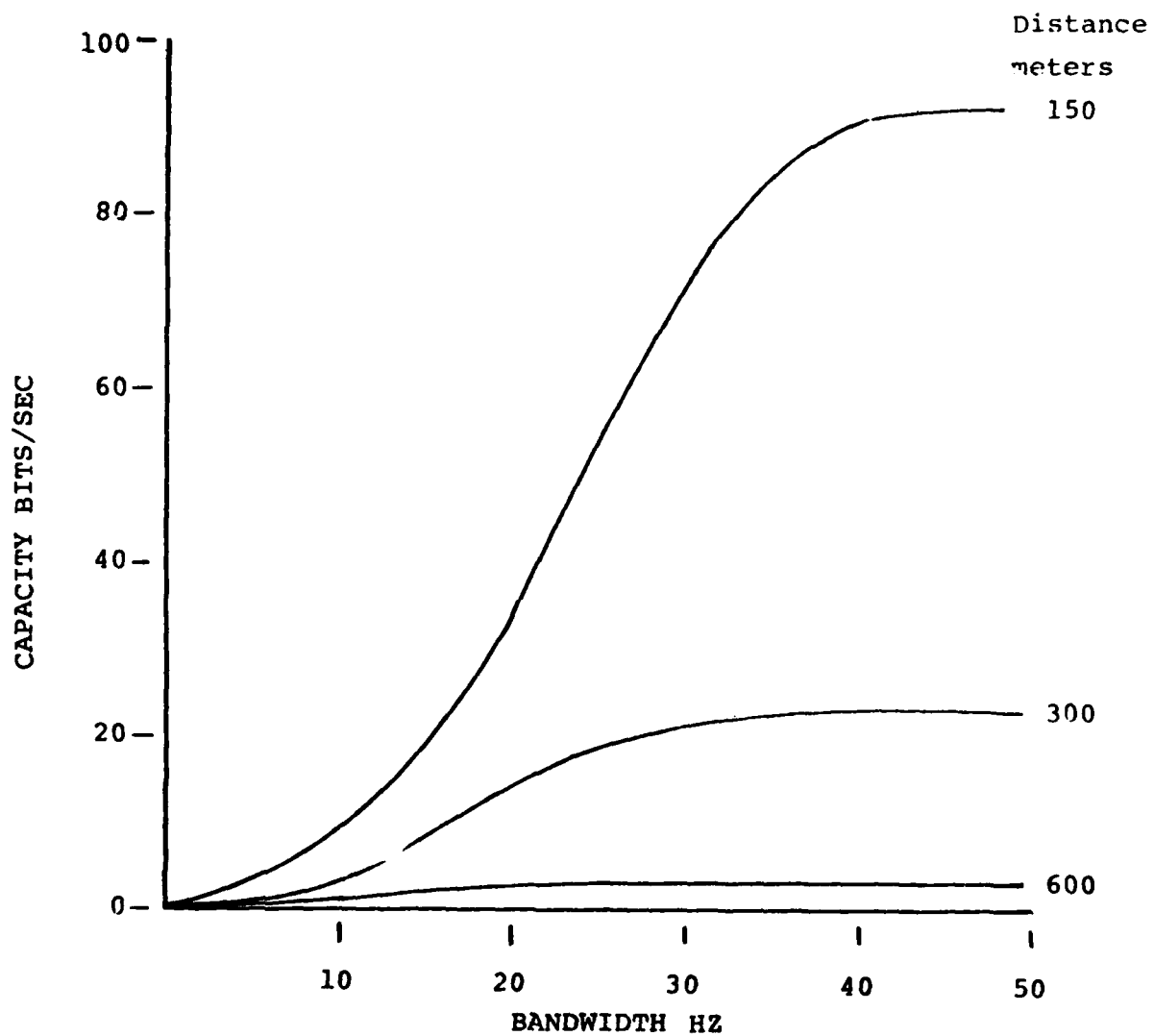GROUND CUTOFF FREQUENCY

Figure 19
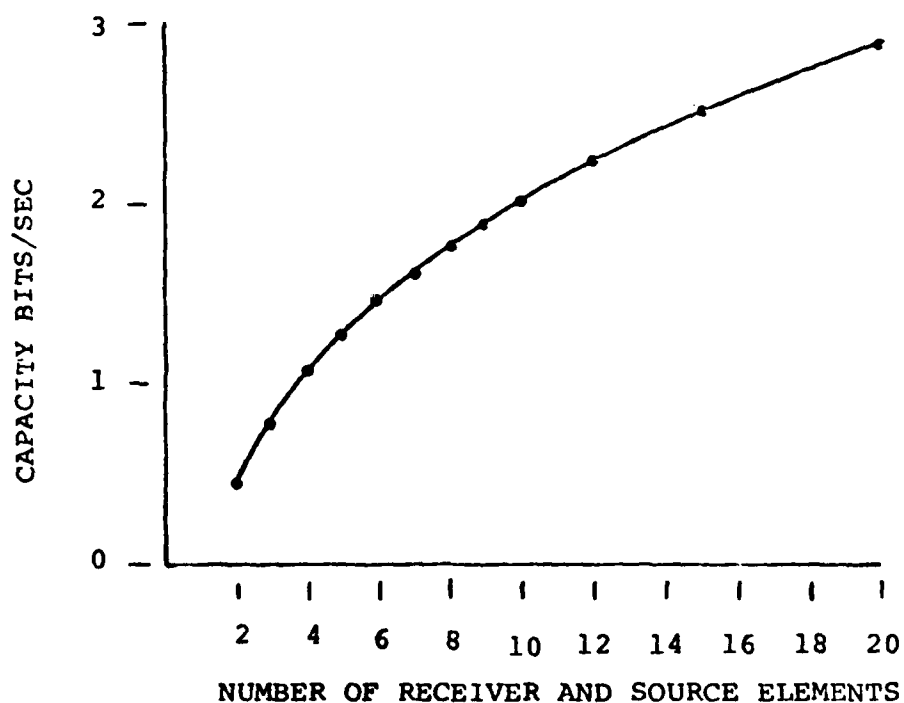
38

Source 31.6 Newtons rms
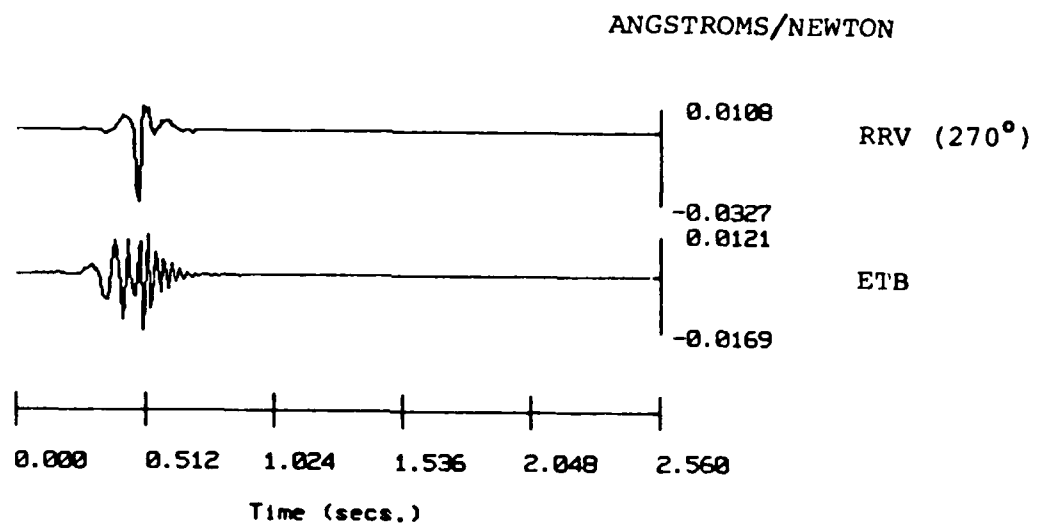

CHANNEL CAPACITIES: WIDE BAND SOURCE
RAILROAD VALLEY

Figure 20

Source Strength   1.5625 Newtons rms
Range   300 meters
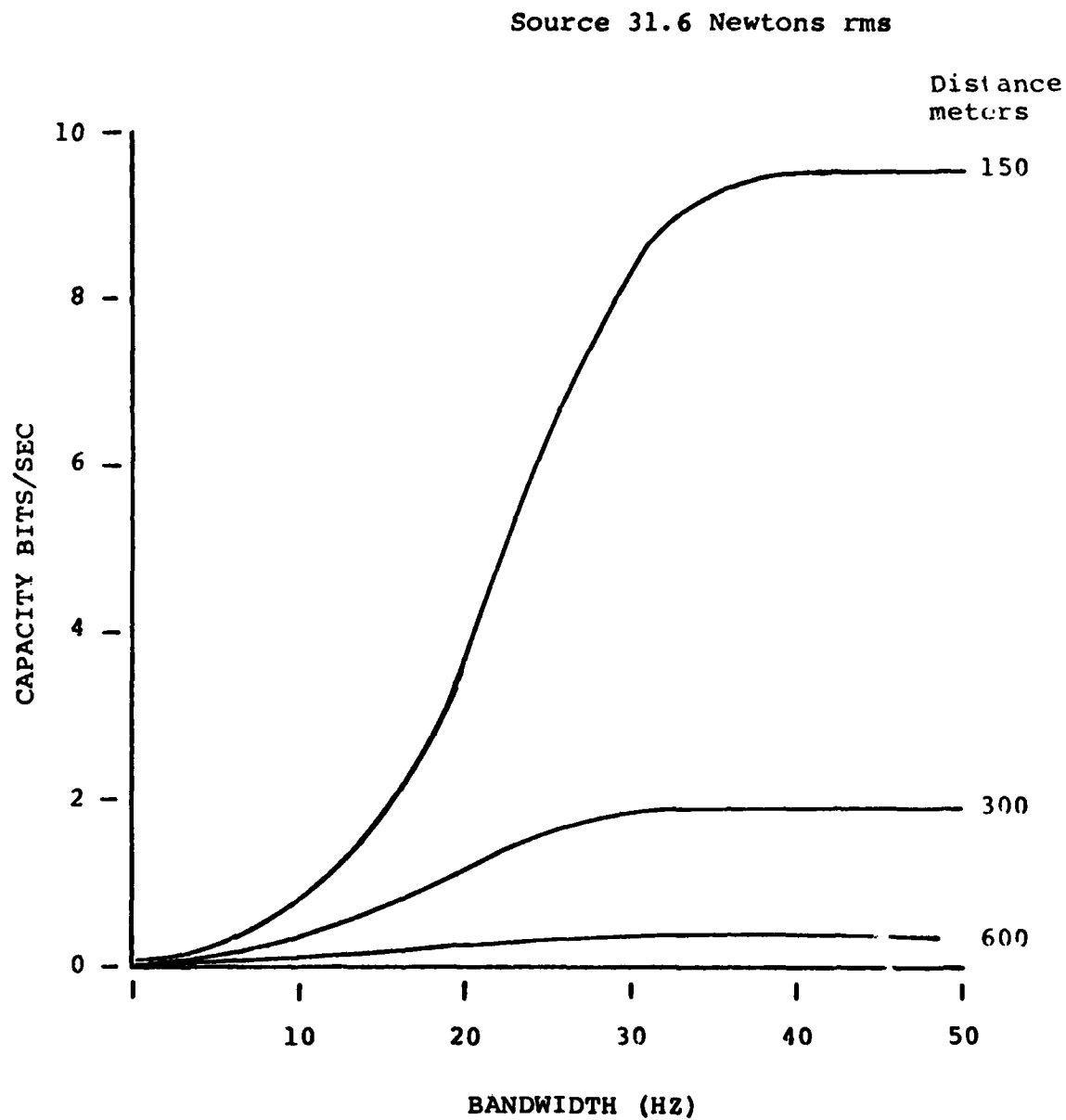Bandwidth   1.0 Hz

EFFECT OF ARRAYS

Figure 21

ANGSTROMS/NEWTON

RRV (270°)

ETB

Range= 150 meters

EFFECT OF SITE

Figure 22

Source 31.6 Newtons rms

CHANNEL CAPACITIES: WIDE BAND SOURCE
JACKASS FLATS

Figure 23

GLOSSARY OF TERMS

A	Source Amplitude
c	Phase Velocities
C	Capacity
db	Decibel
E	Goodness of Fit
f	Frequency Hz
tg	Group Delay
tp	Phase Delay
G	Green's Function
G_{33}	Vertical Displacement of Ground Surface at a "Large" Distance
i	$\sqrt{-1}$
j	Mode Number
K	Wave Number
k'	Trial Wave Number
km	Kilometer
$N(o,s^2)$	Zero Mean, Normal Process
P_{nn}	Power Spectra of Noise Process
P_{ss}	Power Spectra of Signal Process
Q	Material Quality Factor
r	Distance
rms	Root Mean Square
s^2	Variance
t	Retardation Time

GLOSSARY OF TERMS

T	Source Time
T'	Time
t_p	Wave Phase Delay
t_g	Wave Group Delay
U	Group Velocity
ω	Angular Frequency

END

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